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Antarctic blue-ice moraines: analogue for Northern Hemisphere ice sheets?

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Abstract

This paper reviews the distribution, character and age of blue-ice moraines in Antarctica and asks whether there are implications for the study of former Pleistocene ice sheets in the Northern Hemisphere. Blue-ice forms where acceleration of downslope katabatic winds removes snow and causes ice to ablate. Upward ice flow compensates for the surface ablation and in some places brings rock debris to the surface to form a blue-ice moraine. Blue-ice moraines occur where topography focuses katabatic winds, notably outlet glaciers cutting through mountains and in the lee of nunataks and escarpments nearer the coast. Many Antarctic blue-ice moraines have been accumulating for millions of years. The cyclic growth and decay of Pleistocene ice sheets and the dominance of surface ablation near the ice-sheet margins are clearly different, yet there are aspects that apply to Pleistocene ice sheets. Based on Antarctic blue-ice deposits, equivalent deposits associated with former Pleistocene ice sheets are likely to: (1) lie in topographic sediment traps such as in side valleys or embayments next to outlet glaciers, (2) occur in the lee of mountains, (3) display a morphology indicating ice flow into the embayment or towards the mountain front, (4) include a wide range of lithologies derived from the inland ice sheet, yet consist wholly of local debris in places, (5) accumulate a thick deposit perhaps over successive glaciations. Further, (6) the location and intensity of moraine formation will change spatially and vertically in response to changes in the relative elevation of the surrounding mountains and its effect on ice flow. The extent to which these criteria will help in interpreting the behaviour of Pleistocene ice sheets is uncertain. But we use examples from the Greenland, Laurentide and Eurasian ice sheets to suggest that the concept of enhanced ablation by katabatic winds encouraging surface moraine formation helps resolve several puzzles.

Key words

Pleistocene, Glaciology, Geomorphology, Blue-ice moraines, Antarctica, Greenland, Northern Hemisphere Ice Sheets, Topographic sediment traps

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Introduction

The asymmetry between the presence of a continental ice sheet in Antarctica and the exposed beds of former continental-sized Pleistocene ice sheets in North America and Eurasia has intrigued geoscientists since the days of James Croll (1879). In Antarctica we have an ice sheet available for study but a bed that is less well known than the landscape of Mars; in the Northern Hemisphere we have easy access to the bed but have to infer the behaviour of former ice sheets. The studies in different hemispheres have tended to be developed separately by glaciologists/geophysicists in Antarctica and Quaternary geoscientists in the Northern Hemisphere. Increased interaction between these two groups of scientists enhances the progress of both groups of studies.

This paper focuses on blue-ice moraines on the surface of the ice sheet in Antarctica and, following Hättestrand et al. (2008), asks whether there are lessons that may help in interpreting deposits on the beds of former Pleistocene ice sheets in the Northern Hemisphere. In Antarctica, blue-ice areas occur where the ice sheet is subject to wind velocities sufficiently strong and focused to erode snow and create surface ablation. The winds are katabatic and reflect the flow of dense cooled air guided by topography (Fig 1). In Antarctica the pattern of flow is approximately radial from the main ice domes with convergent flow into the Weddell and Ross Sea embayments and into the Lambert basin (Parish & Bromwich, 1987). Wind velocities are highest in winter and increase from the interior towards the coast where they can exceed velocities of 200 km per hour. These are the winds of Douglas Mawson's *The Home of the Blizzard* in which the base hut on the coast of Adélie Land experienced an average wind velocity of 80 km per hour for the first year of the Australasian Antarctic Expedition of 1911-1914. In blue-ice areas where the ice sheet laps against nunataks, rock debris can accumulate on the ice surface and at the ice margin. The latter deposits are known as blue-ice moraines.

Background

Blue ice areas (BIAs) were first studied by the Norwegian–British-Swedish Antarctic Expedition to the fringing mountains of Dronning Maud Land in 1949-1952 (Swithinbank, 1959; Schytt, 1961). Interest surged when it was discovered that meteorites were often concentrated in blue-ice areas and easily picked out against the rippled ice surface (Yoshida et al., 1971). This stimulated many search expeditions and within 20 years some 14,000 meteorites had been discovered (Cassidy et al., 1992). These meteorite discoveries encouraged study of the meteorology, ablation and ice dynamics of blue ice and progress is documented in a comprehensive review (Bintanja, 1999). Initial observations of moraines associated with blue ice interpreted them as equilibrium features related to ablation (Hättestrand & Johansen, 2005) or to changing ice dynamics (Chinn, 1994). It became clear that the blue-ice areas were collecting grounds for meteorites falling on the interior of the ice sheet and that they and the containing ice could be old. In turn this discovery led to the idea that blue ice areas could be used as accessible and horizontal ice cores (Sinisalo and Moore, 2010, Korotkikh et al., 2011, Spaulding et al., 2013; Turney et al., 2013). With the development of cosmogenic isotope analysis, attention has more recently focused on the moraines and surface debris in various blue-ice areas and the implications for ice flow and the history of the ice sheet (Atkins et al., 2002: Ackert et al., 1999; Dunbar et al., 2008; Altmaier et al., 2010; Todd et al., 2010; Hein et al., 2016a; Bibby et al., 2016; Bader et al., 2017; Kaplan et al., 2017; Graly et al., 2018; Akçar et al., 2020). There have also been process studies examining structures in the underlying ice (Campbell et al., 2013; Winter et al., 2016; Kassab et al., 2019).

In this paper we first review the distribution and nature of blue ice and blue-ice moraines in the cold dry polar climate of Antarctica and identify key characteristics. Then, following a discussion of the main similarities and differences between the Antarctic Ice Sheet and former Pleistocene ice sheets, we identify similar moraines on the current Greenland Ice Sheet. In the final section we explore the relevance of our review to study of the former Laurentide, Fennoscandian and British ice sheets.

Blue-ice areas

Satellite observations in Antarctica reveal two main types of blue-ice area, firstly, interior zones associated with steepening and convergent ice-surface slopes and, secondly, those associated with mountains and nunataks in both the Transantarctic Mountains and mountains towards the coastal margins of Antarctica. The first interior group is the most extensive and occurs where the ice-surface slope steepens as ice flows into the head and flanks of major outlet-glacier basins. These locations include the Lambert, Recovery and Byrd glacier basins. Such steepening locations cause the katabatic winds to accelerate. These areas are estimated to account for 2.7 – 6.6% of the surface of the Antarctic Ice Sheet (Das, et al., 2013). Blue-ice moraines and, indeed, meteorites are rare or non-existent in such central blue-ice locations.

The second group comprises a mosaic of blue-ice areas associated with wind flow over mountains protruding through the ice. Prominent blue-ice areas occur in the Transantarctic Mountains and Dronning Maud Land while smaller fields are common around Antarctica, for example in northern Victoria Land (Corti et al., 2003). Further examples occur in the Heritage Range in the southernmost Ellsworth Mountains, where numerous ridges and hills protrude through the ice sheet by 150-200 m and lie transverse to the katabatic winds sweeping towards the Weddell Sea. Blue-ice occurs on the lee side of each of the seven most southerly hill massifs (BAS, 2004).

The process of ice flow and its relation to ablation were illustrated by study of the meteorite-bearing ice in the Allan Hills near the Dry Valleys in the Transantarctic Mountains (Whillans and Cassidy, 1983). Here, ice flows from central Antarctica and terminates at a site high in the Transantarctic Mountains. Modelling suggested that ablation by strong winds near the ice margin causes upward compressive flow exposing ice with ages up to ~600 ka. Assuming active ice and an ice-surface gradient towards the margin, the rate of upward flow will be related to the rate of ablation. In general, rates of ablation range from 3–35 cm per year with the lowest rates above 1200 m and highest rates at low elevations (Bintanja, 1999). In the blue-ice areas of the Heritage Range at an intermediate elevation of around 800 m, where mean annual temperatures are around -28^{0} C (Dahe et al., 1994), ice ablation of blue ice is estimated to be 15-20 cm water equivalent per year (Casassa et al., 2004). Most ablation is by sublimation and the altitudinal gradient reflects both the effect of warming temperatures with decreasing elevation and the increase of katabatic wind velocities towards the coast. At low elevations on certain days there may be additional surface melting induced by the lower albedo of blue ice compared to snow. The importance of wind velocity and its deflection by topography in causing ablation has long been recognized. Mills et al (2019) compared the results of a simple snow-drift model based on the way topography causes acceleration and reduction of wind velocity against the observed pattern of snow accumulation and blue ice in the Patriot Hills, southernmost Ellsworth Mountains. It is remarkable to see how well a simple wind deflection model is able to replicate the observed pattern.

Blue-ice moraines

Surface debris and moraine ridges are best developed in two topographic situations. The first group, common at higher elevations, comprises blue ice in embayments or side valleys beside outlet glaciers that funnel katabatic winds over mountain ranges. Good examples occur in the Transantarctic Mountains and the high escarpments of Dronning Maud Land. In such situations ice from the outlet glacier spreads into the embayment or side valley and flows up-valley. Ablation by katabatic winds brings debris to the surface where it accumulates, often in a series of arcuate loops (Kassab et al., 2019). Dating shows the samples may accumulate over millennial time scales and increase in age from the exposed glacier ice towards the margin. Good examples occur in the Schüssel area of Dronning Maud Land where ages extend as far back as 8 Ma (Altmaier et al., 2010). Similar blue-ice moraines occur in an embayment in the Transantarctic Mountains near Mt. Achernar adjacent to Law Glacier (Kaplan et al., 2017); here ages rise to 550 ka with increasing distance from the ice margin (Fig 2). In Ong Valley, a tributary to Argosy Glacier also in the Transantarctic Mountains, arcuate moraines range in age from 11-13 ka near the glacier margin to at least 1.52 Ma with increasing distance (Bibby et al., 2016). And it is worth pointing out that the ancient Miocene ice covered with rock debris in Beacon Valley, McMurdo Dry Valleys, is in a similar side valley beside Taylor Glacier, an outlet glacier crossing the Transantarctic Mountains (Fig. 3). In this latter case, the age of debris-covered ice was dated by overlying volcanic ash as > 8 Ma (Sugden et al., 1995; Kowalewski et al., 2006) and, based on the similarity of the lithological content to other dated tills, at > 13.6 Ma (Marchant et al., 1993). In retrospect this debris-covered Beacon Valley ice is likely to have formed originally as a blue-ice moraine nourished mainly by Taylor Glacier.

The second location that favours blue-ice moraines is in the lee of mountains and ridges transverse to ice flow. The topographic barrier accelerates wind flow. Most ablation is near the foot of the mountain slope or escarpment and decreases downwind over a matter of km. In turn this pattern of ablation may be sufficient to cause local landward flow of ice quite different to the overall direction of glacier flow. The blue-ice moraine at the foot of the northern flank of the Patriot Hills in the southernmost Ellsworth Mountains has been studied in some detail (Fogwill et al., 2012; Westoby, 2015; Winter et al., 2016; Woodward et al., 2021?). Here ablation is highest at the foot of the mountain slope and tails off over a distance of 2 km. In response, the glacier surface slopes towards the mountain and ice at the margin flows directly landward at an angle to the flow of the trunk glacier. The blue-ice moraine borders the mountain flank for 6 km and is up to 300 m wide in embayments (Fig. 4). At the ice margin is a zone of folded debris bands and isolated boulders exposed on the glacier surface. Adjacent to the exposed ice is a pitted ramp rising gently inland covered thinly with debris and with large boulders resting on pedestals of ice. This gives way to a zone of continuous and boulder-rich ridges up to 10 m high orientated parallel to the land margin. Ground Penetrating Radar shows upward trending bands of debris in the glacier beneath the surface deposit. Cosmogenic isotope age profiles reveal that boulders on the blue-ice surface have zero age exposure and thus are likely to have been ablated to the surface recently. Once on the moraine, there is a scatter of boulder exposure ages ranging from a few thousand years to 70,000 years.

Other morphological variants of blue-ice moraines occur at the foot of neighbouring massifs in the southernmost Ellsworth Mountains (Hein et al., 2016b). In the Independent Hills there is a band of ice nourished by overspilling ice between the moraine and the base of the mountain front; the moraine extends several km downglacier diverging from the mountain front as overspilling ice is added progressively. Nearer the Marble Hills the mountain front moraine is drawn out down-glacier by a larger flow of overspilling ice.

The rock debris in blue-ice moraines is derived from both the glacier base and adjacent mountain slopes. The subglacial origin of the Mt. Archernar moraines in the Transantarctic Mountains is established from isotopic evidence of basal freezing (Graly et al., 2018), lithological studies (Bader et al., 2017) and GPR survey of ice structures (Kassab et al., 2019). In both cases entrainment was from beneath Law outlet glacier. In the Patriot Hills, the striated nature of many boulders and their association with folded debris bands implies a basal origin (Fogwill et al., 2012), a conclusion backed up by radar surveys showing debris extending 800 m to the base (Hein et al., 2016a). Local rockfall can also contribute. In the Patriot Hills locally nourished glaciers and rock glaciers flow into the blue-ice zone contributing rockfall material (Woodward et al., 2021). This means that zones of wholly local lithologies occur within the wider spread of lithologies associated with far-travelled material. Blue-ice moraines in Scharffenbergbotnen, Dronning Maud Land, are dominated by local rockfall (Hättestrand & Johansen, 2005). Other typical examples of locally sourced glacier debris and rockfall on the surface of blue ice in the Sarnoff Ranges, Marie Byrd Land, are shown in Figure 5.

Thinning of the Antarctic ice sheet since the Last Glacial Maximum means that it is possible to look at the characteristics of stranded blue-ice moraines. In the southernmost Heritage Range the ice-sheet surface fell ~400 m from near its Last Glacial Maximum elevation after ~10 ka (Hein et al., 2016b). There are four notable points. First, the thinning has left a veneer of till patches and little-weathered boulders scattered over the landscape. Second, the volume of debris and its lithological make-up vary from place to place and with changing elevation. A likely reason for the variations is that, as the ice surface lowers, the relative elevation of the mountain barrier to the ice-sheet surface changes. This changing topographical relationship changes the intensity and location of katabatic wind velocities, the pattern of ice flow, the location of debris entrainment and thus the distribution of blue-ice moraines in the lee. Thirdly, in certain situations the degree of weathering and dating show that fresh boulders have been deposited on a surface of pre-existing boulders. In this situation it appears that pre-existing boulders have survived inundation by ice, perhaps because the ice was cold-based. Finally, in one location in the Marble Hills buried ice lies beneath a veneer of rock debris; radar and the arcuate surface morphology shows the ice is thick enough to flow down the local topographic slope (Woodward et al., 2021?). The implication of this is that surface boulders will move and be freshly exposed as the ice wastes away. In the Marble Hills example, the stranded ice has survived 10 ka since deglaciation. Perhaps the > 8 Ma-old ice in Beacon Valley is an extreme example of such survival. If so, this would explain why cosmogenic isotope analysis of surface stones yields younger ages (Ng et al., 2005).

Key characteristics of relict blue-ice moraines

How might one recognize deposits associated with blue ice of former Pleistocene ice sheets in the Northern Hemisphere? Such a question invites comparison with a body of literature on controlled moraines (Evans, 2009; Benn and Evans, 1998). The latter are so named because their morphology reflects the structures in the underlying glacier and in this sense are controlled by the distribution of debris in the underlying ice. Such moraines typically occur near glacier margins in the northern Arctic where debris is incorporated at the base and is brought to the surface in debris bands where it ablates. Following Weertman (1961), it is thought that ice passing from a warm-based to cold-based basal regime favours entrainment by freezing whilst compressive flow near the ice margin raises the debris to the surface (Hooke, 1973; Holdsworth, 1973). Such marginal controlled moraines are common in the northern permafrost zones of Arctic Canada and Greenland (O'Cofaigh et al., 2003). Whereas there are similarities between such controlled moraine and Antarctic blue-ice moraines in that underlying structures in the ice are important, the key difference is that katabatic winds in Antarctica determine where blue ice occurs and the intensity of surface ablation. In turn this influences the amount and nature of debris that may appear on the surface.

Building on the observations of blue-ice moraines in Antarctica, there are six key characteristics.

Criterion 1. Blue ice moraines areas are associated with outlet glaciers as they traverse peripheral uplands. The Transantarctic Mountains and the mountain escarpment in Dronning Maud Land comprise passive margin escarpments dissected by outlet glaciers that focus katabatic winds from the ice-sheet interior. The most common locations for surface debris accumulation are where trunk glaciers can expand and flow into embayments or side valleys. In effect such blue-ice areas trap sediment from the outlet glaciers.

Criterion 2. Blue-ice moraines in Antarctica occur in the lee of nunataks or mountains protruding through the ice sheet. One favoured location is near the ice sheet interior where ice surface gradients are low and ice surface elevations change slowly, as in the case of Mt Waesche in Marie Byrd Land (Ackert et al., 2013); another is near the thinner ice sheet margin where wind velocities are highest, as in the Patriot Hills in the southernmost Ellsworth Mountains, Antarctica. Ablation, highest at the foot of the mountain, means that debris-bearing ice flows towards the mountain front in the lee. Compressive ice flow, compensating for surface ablation, brings debris towards to the surface where it accumulates in a sediment trap.

Criterion 3. The morphology of the debris accumulating in such sediment traps will reflect flow into the embayment or towards the mountain front. In the case of moraine ridges intruding into a side valley the arcuate forms will loop up-valley. This orientation is opposite to that expected if the moraines were formed by local glaciers flowing down the valley. In the case of a mountain front any ridges will lie parallel to the ice margin. In the case of rockfall debris there may be a scatter of surface boulders.

Criterion 4. A sediment trap will contain a range of lithologies derived from upstream parts of the glacier basin. Of course the main control will be the lithologies exposed in the glacier catchment, but the configuration and effectiveness of the sediment trap will also play a role. If there is a source for local ice at the head of the embayment or escarpment such as a corrie glacier, then the far-travelled debris may be displaced by locally derived bedrock derived from the backwall. In the latter case, the blue-ice moraine could be comprised wholly of local lithologies. In warmer environments where there is surface melting one would expect fluvio-glacial and lacustrine material to be in the mix; the ice surface gradient towards the land would concentrate meltwater at the margin while ice-dammed lakes could occupy embayments.

Criterion 5. The deposit is likely to be thicker than debris in the surrounding area and comprise materials of different ages. Given the dominant control of topography on the location of blue ice moraines, it seems reasonable to suggest that the sediment traps develop in the same place at certain stages of glaciation and deglaciation over successive glacial cycles. If so, an expanding glacier is likely to override pre-existing debris, incorporating some boulders, preserving others, while depositing a fresh cover of material. Where thick enough, this ice-cored debris may itself flow down the local slope and persist for some millennia. An implication for a future fieldworker is that boulders sampled for terrestrial cosmogenic nuclide assays may yield a broad scatter of ages, with some relating to the last glacial event and others to previous glaciations.

Criterion 6. The characteristics and volumes of sediment will vary in both vertical and horizontal dimensions. The growth and decay of ice sheets and their changing dimensions and elevation during the climatic oscillations of the Pleistocene means that the location and effectiveness of ablation would also change. As an example, assume a decline in the surface elevation of an ice sheet from a thickness that covers a mountain massif to the final wasting of the adjacent outlet glaciers in surrounding valleys. Enhanced ablation by katabatic winds would begin only when the mountain emerges sufficiently to modify wind flow on the ice-sheet surface; it would cease when the relationship between the falling ice surface and the emerging topography re-routed the katabatic winds. At an intermediate stage, assuming the presence of a local corrie glacier, there would be a peak of local glacier sedimentation as the unsupported backwall weathers and debris accumulates on the falling ice surface. In such a situation and depending on location, the moraine could comprise either far-travelled or wholly locally derived material and vary considerably in thickness and/or characteristics.

Differences and similarities between the Antarctic ice sheet and Northern Hemisphere ice sheets

Before reviewing evidence for the former existence of blue-ice moraines in the Northern Hemisphere, it is important to discuss differences and similarities between ice sheets in the different hemispheres.

Onset and duration of glaciation

The Antarctic Ice Sheet first developed at the greenhouse-ice house transition in the Eocene (Kennett, 1977; DeConto and Pollard, 2003). For the last 15 million years the ice sheet has been a constant presence especially in East Antarctica (Balco et al., 2014). In West Antarctica dating of blue-ice moraines shows that the ice sheet survived on mountain massifs during the last interglacial in Marie Byrd Land (Korotkikh et al., 2011) and in the southernmost Ellsworth mountains, findings that agree with models showing a persistent core but fluctuating ice margin (Hein et al., 2016a).

In contrast, the Greenland Ice Sheet was extensive in the upper Miocene (Thiede et al. 2011) but fluctuated in its thickness and extent thereafter, and may have largely melted during Pleistocene inter-glacials (Schaefer et al., 2016). The Laurentide Ice Sheet developed at 3.5 Ma (Gao et al. 2012), and fluctuated in extent thereafter following orbital forcing . The Eurasian Ice Sheet first developed at 2.75 Ma (Kleiven et al., 2002). Two of its component ice masses, the Fennoscandian Ice Sheet and the British Isles Ice Sheet reached maximum extents after 0.5 Ma (Ehlers et al., 2018), and fluctuated in thickness and extent through cold stages, disappearing in interglacial periods. The Antarctic Ice Sheet was and remains largely marine-terminating. The Greenland Ice Sheet and the western and northern margins of the Eurasian Ice Sheet were similar. The southern margins of the Laurentide and Eurasian ice sheets, however, terminated on land.

Ice sheet dynamics

The relative stability of large parts of the Antarctic ice sheet stands in contrast to the dynamism of parts of the former Greenland, Laurentide and Eurasian ice sheets since 6-3 Ma. In the Northern Hemisphere, the patterns and rates of ice thinning and retreat since the last Maximum have been dramatic. Both the eastern sector of the Laurentide Ice Sheet and the south-western sector of the European Ice Sheet experienced near collapse during the rapid warming that followed the Younger Dryas cold event (Carlson et al., 2008; Brendryen et al., 2020). Even in continental sectors, the Laurentide and European ice sheets thinned by over ~1 km over 0.7-1.6 ka timescales (Barth et al., 2019; Corbett et al., 2019). The residence times for ice margins on mountain massifs in the Antarctic may extend over 10^6 to 10^4 year timescales: in the case of Northern Hemisphere ice sheets, a thinning ice margin may remain at a given elevation and location only for 10^2-10^1 years.

Ablation

A further contrast between Antarctica and former Pleistocene ice sheets is that the latter had a peripheral southern zone of surface ablation where melting would have been an important process of ablation. The Greenland Ice Sheet is a useful analogy. Here, there is surface ablation below the Equilibrium Line Altitude (ELA) at an elevation of around 1450 m. Summer melting, enhanced by wind, is an important process of ablation. On lowland margins in Greenland the ablation zone may extend inland from the ice margin for tens of km. In the years 1958–2017 the vast majority of the ablation area saw the net surface ice lost per year range from zero at the equilibrium line to 1000-

2000 mm per year, depending on latitude (Noël et al., 2019). Values increase further at the ice margin where the ice surface is steepest. On high margins above the equilibrium line, such as East Greenland, blue ice is exposed and associated with winds and ice converging at the head of outlet glaciers flowing through the mountains (Haack et al., 2007).

The implication of the above for Pleistocene ice sheets is that, although the relationship of accumulation to ablation is different to that in Antarctica, the same principles of enhanced ablation due to katabatic winds might apply within the ablation zone. In Antarctica most of the ice sheet experiences net accumulation and blue-ice moraines are associated with topographically scattered patches of persistent net ablation by sublimation. In the case of Northern Hemisphere ice sheets similar patterns of sublimation may have occurred at high elevation and northern margins. But at lower, southern elevations the main role of topography on wind flow may be to create local hot spots of enhanced ablation by melting. In such cases the effect of ablation by wind is in addition to other forms of ablation. If the rate of ablation in such locations is significantly more than that of the surroundings, then compressive ice flow could build and maintain debris on the surface to form moraines on bare ice. Surface ice in such ablation areas is affected by melting and the accumulation of atmospheric dust and no longer looks blue; thus we substitute the term bare ice, rather than blue ice, for areas affected by surface melting.

Katabatic winds

The strength of katabatic winds on the Antarctic Ice Sheet reflects both its continental size and its cold location centred on the South Pole. At their maximum both the Laurentide and Scandinavian ice sheets were of comparable size to the Antarctic Ice Sheet but centred in northern mid-latitudes. In the case of the Laurentide ice sheet study of proxy palaeo-temperatures surrounding the ice sheet point to modest cooling and is best explained by the occurrence of adiabatic warming by katabatic winds (Bryson and Wendland,1969; Sugden, 1977). Further, there is evidence of katabatic winds from ventifacts and wind-polished surfaces surrounding former ice sheets, for example in the case of the Laurentide Ice Sheet (Thiesmeyer & Digman, 1942; Demitroff, 2016), the Fennoscandian Ice Sheet (Schytler, 1995; Lagerbäck, 2007) and the British Ice Sheet (Christiansen, 2004). We can speculate that the large size of Northern Hemisphere ice sheets is likely to have created strong katabatic flows down the ice surface, but that their lower latitudes than Antarctica would imply less extreme winds.

Surface ablation by katabatic winds may also have characterised many intermediate stages of glaciation during cycles of growth and decay as, for example, when ice sheets were constrained to the Scandinavian peninsula or the Scottish mainland. Here it is useful to look at the Greenland Ice Sheet which is in a similar latitude to the main mid-latitude Pleistocene ice sheets. Bromwich et al. (1996) show that katabatic winds flow from the gently sloping interior of the Greenland ice sheet, including the narrow southern dome, towards the steeper coastal margins. As in Antarctica, winds speed up as they converge into the head of large outlet glaciers and fjord basins. The winds are strongest in winter when radiative cooling is at a maximum. Wind speeds of >9 m s^{-1} occur on northeastern slopes of the Greenland ice sheet (Ettema et al., 2010).

An additional factor for ice sheets in a westerly mid-latitudinal climate involves synoptic pressure gradients that can accentuate the katabatic effect on the eastern lee flanks of an ice sheet. Noël et al. (2019) noted how increased precipitation on the western flank of the north Greenland Ice sheet was linked to a föhn effect that amplified rates of ice ablation in the east. Another example comes from the ice caps of Patagonia in South America. Here, storms in the southern westerlies create high rates of orographic accumulation on the exposed western slopes of the ice caps while the resulting föhn winds in the lee enhance rates of ablation on the eastern glaciers (Warren et al., 1993).

Blue-ice and bare-ice moraines on Northern Hemisphere ice sheets?

The outline of blue-ice moraine features in Antarctica above has possible implications for the location, lithology and age of glacial deposits in the formerly glaciated areas of the Northern Hemisphere. Below we apply the criteria listed above to seek evidence for blue- and bare-ice moraines on Northern Hemisphere ice sheets, namely the current Greenland Ice Sheet and the former Fennoscandian, Laurentide and British Isles ice sheets.

Greenland Ice Sheet

It is a useful step in the argument to ask whether there is evidence of surface moraines on the ice sheet in Greenland that might be related to katabatic winds. We focus on the land boundary of the ice sheet in West Greenland where there are nunataks and ridges protruding through the ice and have avoided the complexities of the fjord landscapes of the east.

In a detailed study in northwest Greenland, Hooke (1970) showed that the presence or absence of surface moraine depended on the orientation of the ice-sheet margin in relation to the prevailing katabatic winds. In windy locations that erode the ice surface, upward ice flow brings subglacial material to the surface. In this northern location most of the ablation will be by sublimation. (Criteria 1, 3, and 6 satisfied)

Perusal of satellite imagery in west Greenland reveals several sites with exposed bare ice and surface moraine (Fig 6). A bare-ice zone with surface debris occurs in the western lee of J.A.D. Jensens Nunatakker situated 20 km inland from the ice-sheet edge between the coastal settlements of Paamiut and Qeqertarsuatsiaat (Fig 6,1). A bare ice area occurs in the lee of five nunataks over a distance of some 10 km and extends several km to the lee. Ridges of moraine run along the foot of the nunataks on the lee side and in one location the moraine is offset by overspilling ice, as in the case of the southernmost Ellsworth Mountains. In another location, ice flowing through a gap in the nunataks has drawn out an lobate moraine ridge that intersects with further ridges down-ice. Finally, a lake and a calving margin in ice flowing towards the nunatak occur in an embayment. Here the ice flow towards the nunatak is directly opposite to that of the surrounding ice sheet surface. The lake is interesting because it implies that the principles of enhanced ablation derived in Antarctica also apply in a warmer setting with meltwater. (Criteria 2, 3, and 6 satisfied)

Examples of moraine accumulating in embayments and side valleys adjacent to an outlet glacier can be seen on the western flanks of the ice sheet in northern Melville Bugt at 75^0 32’ N., some 70 km north of Kullorsuaq (Fig 6,2). An outlet glacier, with a bare ice surface, drains westwards from the ice sheet into Melville Bugt. Ice flows into several embayments on its northern flank. In one there are five arcuate moraine ridges separated by glacier ice looping into the embayment; in another is a spread of surface rock debris marked by ridges that also loop into the embayment. Both patterns are similar to those in topographic embayments beside outlet glaciers in Antarctica, as for example in Figure 2. (Criteria 1, 3 and 6 satisfied)

Finally, one can point to the link between the large volume of debris accumulating in embayments adjacent to major outlet glaciers. Such deposits are revealed by retreat of the ice sheet since around 1880 (Weidick, 1968). For example, the glacier flowing into Kangilinnquit fjord in southwest Greenland has accumulated significant amounts of debris in embayments adjacent to and facing up-glacier (Fig. 6,3); the adjacent bare-ice surface reflects wind ablation converging into the outlet glacier catchment and fjord. In the case of Jakobshavn Isbrae, recent retreat has exposed thick lacustrine and moraine deposits in an embayment on its southern flank (Fig 6,4). The sheer volume of debris is in sharp contrast to the surrounding eroded bedrock landscape. Such concentrated accumulations of debris could point to the role of katabatic winds in enhancing surface ablation adjacent to major outlet glaciers. (Criteria 1, 3, and 6 satisfied)

Many of the criteria for recognition of blue-ice moraines in Antarctica are met in these Greenland examples. We conclude that the Greenland Ice Sheet does indeed carry bare-ice moraines and in topographically similar situations to those affected by katabatic winds in Antarctica. The next step is to ask whether these ideas could help in understanding glacial deposits from Pleistocene ice sheets.

Fennoscandian and Laurentide ice sheets

Here we look at the possible implications of the Antarctic and Greenland experience for both blue- and bare-ice moraines formed by Pleistocene ice sheets. It is helpful first to look at conditions where full near-maximum ice sheets existed, second at the possibilities during cycles of growth and decay and thirdly a local Scottish example. In some examples there is evidence of blue-/bare-ice moraines; in others we outline possibilities.

Blue-ice moraines and near maximum ice sheets

Remarkably, former blue-ice moraines complete with their original glacial ice cores are still present in the northern permafrost zones of Arctic Canada. The northern fringes of the main Laurentide Ice Sheet exhibit extensive moraine belts 10-40 km across consisting of hummocky moraine and lake basins bordered on the interior up-ice flank by streamlined bedforms (Dyke and Evans, 2003). In places buried ice can be seen to underlie the hummocks and reveals isotopic and englacial structures with debris bands characteristic of ice sheets (Mackay, 1983; St-Onge and McMartin, 1995). The hummocky terrain is thought to relate to the ablation of englacial debris incorporated at the transition from a warm-based streaming ice to cold-based based ice. Detailed mapping on Victoria Island reveals belts of hummocky moraine and meltwater deposits that mark the progressive retreat and thinning of the trunk outlet glaciers in the adjacent straits (Dyke and Savelle, 2000; Dyke et al., 2003). There are particular concentrations of debris along the lateral margin of the trunk glacier flanking the southern shore of Victoria Island (Dyke and Savelle, 2000). The role of katabatic winds in such patterns is unexplored. One can speculate that strong katabatics would be expected near successive ice margins of the full ice sheet and that the resulting high surface ablation boosted the processes of upward compressive flow and debris entrainment. The winds could help explain the sheer dominance of controlled moraine in this zone. Funnelling of katabatics along the trunk glaciers in the straits would be expected to enhance ablation and help explain the concentrations of debris at glacier margins. A final point of interest in this northern permafrost zone is that ice from the Laurentide ice sheet is still there and as such its preservation bears comparison with the ancient spreads of blue-ice moraines in Antarctica.

Based on Antarctic experience, we might also expect blue-ice moraines to be associated with outlet glaciers where they cut through the mountains of high passive margins. At the glacial maximum such glaciers dissected the margins of the Laurentide ice sheet in Ellesmere Island, Baffin Island and Labrador (Dalton et al. 2020; Sugden, 1978). The large size of the ice sheet and the high elevation of the mountains imply that main glacier basins would have been the focus of strong katabatic winds. If so, then blue ice moraines could have formed in embayments or side valleys. An increasing number of such sites might emerge over time as each outlet glacier deepened its trough or fjord and lowered its surface during successive glacial cycles.

Another common location for blue-ice moraines in Antarctica is in relation to nunataks or mountains protruding through the ice, especially where the ice thins towards the ice sheet margins, as in the Patriot Hills in the southernmost Ellsworth Mountains, Antarctica. There are many such locations near the margins of Pleistocene ice sheets that would have experienced strong and persistent katabatic winds.

Blue-/bare-ice moraines and intermediate glaciation

The cirque/corrie basin infills in the Khibiny Mountains in the Kola Peninsula seem to provide a good example of blue-ice moraine accumulation at an intermediate stage of deglaciation. Hättestrand et al. (2008) suggested the infills resulted from blue-ice sublimation at the margin of the Scandinavian ice sheet during deglaciation. The deposits meet several of the criteria inferred from Antarctic blue-ice moraines. In this case the thinning ice sheet exposed nunataks (criterion 2) and flowed up-valley into the corrie basins (3). In terms of the criteria, the deposits are tens of metres thick (5), they show arcuate forms looping into the corrie (3) and they contain far-travelled erratics that in places merge with local lithologies (4). Lineations on some pre-existing deposits reflect overriding and suggest that deposition occurred during more than one glacial episode (5). In several cases there are morphological features indicating subsequent down-valley flow of debris and buried ice. All these characteristics help make the case that blue-ice deposits may well be a feature of the dry polar zone of the Fennoscandian Ice Sheet.

Further examples of nunataks emerging centrally because of ice-sheet thinning at a relatively early stage of deglaciation occur at the two locations of Mt. Elgåhogna and Dovrefjell, Norway (Goehring et al., 2008; Lane et al., 2020). In the latter case ice-sheet moraines lap against the mountains and flow into embayments and valleys. A similar phase of early thinning and nunatak exposure occurs in the case of the Cordilleran Ice Sheet in North America (Menounos et al., 2017). In all these cases cosmogenic isotope analysis reveals some anomalously old exposure ages – something that might be expected if katabatic winds helped to create blue-/bare-ice moraines.

Deglaciation of the Scandinavian Peninsula offers an interesting example of the changing relationship between ice-sheet flow and transverse mountain topography during deglaciation. At glacial maxima the Scandinavian ice sheet was centred over the Baltic and flowed westwards across the mountains of the Swedish-Norwegian border. As the main ice sheet in Fennoscandia thinned it exposed the mountain tops and then withdrew from lower eastern slopes. During the early part of the last glacial cycle, moraines formed in the lee of nunataks in the mountains of west-central Sweden, deposited by ice moving towards hill flanks (Kleman et al., 2020) and meeting Criteria 2-6. Heyman and Hättestrand (2006) record instances of ice sheet flow into the emerging valleys building complex moraines. The morphology indicates up-valley flow and subsequent downslope slumping of ice-cored debris. They also record shallow gradient moraines flanking the mountain front. These observations are in agreement with Criteria 2, 3 and 4. Presumably at such a time there would have been katabatic winds flowing down the ice slope with the potential to enhance ablation.. The time available for blue-ice moraine formation, however, was brief. Thinning at estimated rates of ~2 m/a provided short residence times for moraine formation (Heyman and Hättestrand (2006).

Deglaciation: British Isles Ice sheet in the Cairngorm Mountains, Scotland

In the final part of this article we try to assess the value of the concept of katabatic influences on bare-ice moraines in a local context, namely the northern Cairngorms in Scotland. The Cairngorms, with rounded uplands punctuated by corries, comprise a mountain massif underlain by granite in the eastern Grampians (Fig. 7). The Grampian mountains formed an independent ice centre with outflow at glacial maxima merging with ice from the western Highlands flowing generally eastward. The mountains lie on the southeastern flank of Strath Spey which bears erosional marks of a major ice stream flowing north-eastwards towards the Moray Firth. In the Glenmore embayment at the foot of the main Cairngorm massif is a complex of moraines and meltwater features that are part of the margin of a 60 km-long outlet glacier flowing down Strath Spey. On the basis of different approaches and dating techniques, there are different interpretations of the pattern of deglaciation, ranging from ice-sheet stagnation, a stillstand during ice-sheet deglaciation, to active retreat following a late-glacial readvance (Hall et al., 2016).

The puzzlement is related to several features. First, the volume of material is remarkable and involves a wedge of mixed glacial/fluvioglacial/lacustrine deposits up to 60 m thick near the mountain slope and declining in thickness towards the basin floor at Loch Morlich (Fig. 8). A series of individual moraine ridges and meltwater channels are superimposed on top of this wedge of drift and lap around the embayment (Sugden, 1970, Brazier et al., 1996). Secondly, till deposits with far-travelled erratics of schist lap up to an elevation of 800 m or more along the northern slopes of the Cairngorm massif and indicate flow of the ice sheet from the south-west. However, at the same elevation in other places the deposits consist wholly of local Cairngorm granite. Finally, the dating evidence is inconsistent. Cosmogenic isotope measurements on boulders on moraines reveal a scatter of ages ranging from 13.5 – 24 ka (Hall et al., 2016). Moreover, many of the latter ages are older than radiocarbon dates for basal peats in upper Strath Spey that indicate complete deglaciation by 15.0 ka (Ballantyne, 2010).

Many of the puzzling features meet the six criteria for blue/bare-ice moraines outlined above. Suppose that the ice in front of the northern slopes of the Cairngorms had been subject to enhanced ablation by katabatic winds flowing from the ice divide over the Grampian Mountains towards the Spey ice stream. The site is in a topographic embayment on the flank of what was a major ice stream. The mountain front of 300-400 m provides the topographic relief to accelerate down-slope winds and enhance ablation. If the latter caused sufficient surface ablation at the mountain foot, then ice would flow from the main Spey ice stream into the Glen More embayment bringing sediment and depositing ridges around the flanks of the embayment. The unusual thickness of the deposits could represent accumulation over several glacial cycles, as would be expected in a bare-ice sediment trap. The scatter of cosmogenic isotope ages on the deposit is consistent with the idea of bare-ice areas accumulating surface debris for some time before final deglaciation. The age of the youngest cosmogenic isotope outliers may reflect subsequent disturbance of boulders as the debris-covered ice melted out. Finally, the zones of locally derived rocks in front of the northern corries (and beyond arcuate moraines of younger age) may have merged with the far-travelled debris-bearing ice. These corries are close to glaciation today (Kirkbride et al., 2013) and were occupied by ice during deglaciation.

Despite meeting several criteria for blue-ice moraines, the Cairngorm features may well have other explanations. Glacilacustrine sediments in embayments have been widely disturbed by glacitectonics (Brazier et al., 1998; Golledge, 2002) indicating fluctuations along ice margins. Deglaciation of the Strath Spey ice lobe was rapid, with a drop of the ice surface from 800 m to 300 m within the 1 ka resolution of cosmogenic exposure ages (Hall et al., 2016). Hence the residence time for a single moraine on the flanks of the northern Cairngorms was likely a few decades at most. However, the stratigraphy indicates the presence of older sediment that has been overridden by the last ice advance (Figure 8). This sediment is undated but its unusual thickness may relate to a tendency for the Strath Spey ice to repeatedly occupy the same positions on the mountain flanks and to build up thick sediment over multiple glacier advances. This tendency may have been enhanced by katabatic winds draining from the Grampian ice dome and enhancing ablation along the edge of the embayment. In turn this may relate to a topographically guided threshold of stability during glacial cycles of growth and decay.

Conclusion

In the belief that increased communication between Antarctic glaciologists and geoscientists studying Pleistocene ice sheets is worthwhile, we have reviewed findings about blue-ice moraines in Antarctica. We argue that:

1. Subject to enhanced ablation by katabatic winds, blue-ice moraines in Antarctica form in topographic traps adjacent to outlet glaciers and in the lee of nunataks. The moraines include far-travelled sub-glacially derived and local rock lithologies.
2. We identify 6 criteria that characterize these blue-ice moraines and then apply the findings to interpret some deposits associated with Northern Hemisphere ice sheets.
3. We confirm the presence of blue- or bare-ice moraines on the Greenland Ice Sheet which we use as an analogy of former mid-latitude ice sheets in North America and Eurasia; the implication is that such moraines can occur on ice sheets with widespread surface ablation zones.
4. We identify likely and possible locations for blue- or bare-ice moraines on the Laurentide and Eurasian ice sheets.
5. Some local moraines on the Fennoscandian and British Ice Sheets meet many of our criteria, despite rapid thinning of these ice sheets during deglaciation.

Overall, we conclude that the recognition of blue- or bare-ice moraines could help in interpreting some aspects of former Northern Hemisphere ice-sheet behaviour. However, there are many caveats and possibilities for equifinality and it remains to see how helpful the concept is.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution

The authors contributed equally to the concept and writing.

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List of Figures

Figure 1. Reference Elevation Model of the Antarctic Ice Sheet (REMA) and locations mentioned in the text. DEM courtesy of the Polar Geospatial Center. (After Howat et al., 2019).

Fig.2. The blue-ice moraines at Mount Achernar, Transantarctic Mountains. The moraines have accumulated over millions of years and have been eroded from beneath Law outlet glacier, an outlet glacier of the East Antarctic Ice Sheet (background). Photograph by Kathy Licht.

Fig 3. The debris-covered floor of Beacon Valley, McMurdo Dry Valleys, that overlies glacier ice is likely to be a relict blue-ice moraine. Taylor outlet glacier, flowing from left to right in the distance, pushed into the mouth of Beacon Valley. The 8-Ma debris is in mid-valley towards the present ice cliff of Taylor Glacier. The debris further up-valley to the left is underlain by local ice. An ancient stranded lateral moraine on the near slope marks the initial level of the blue-ice moraine.

Fig 4. The blue-ice moraines at the foot of the Patriot Hills, Heritage Range, showing debris bands on the ice, pitted ramp adjacent to the ice and moraine ridges. The snow picks out the presence of splaying crevasses beneath the ridges as the ice flows into the embayment. In the foreground are relict blue-ice moraine boulders from the last stage of deglaciation.

Fig. 5. Left. A local corrie moraine exposed in blue ice where it joins a larger glacier, Mt. Gonzalez, Sarnoff Mountains, Marie Byrd Land, Antarctica. Foliation shows that the basal ice of the corrie glacier is exposed on the inboard side of the debris as a result of surface ablation. Right. Rockfall debris at the foot of The Billboard, Sarnoff Mountains, Marie Byrd Land. The blue ice surface has been covered by a recent snowfall.

Fig 6. Blue- or bare-ice moraines in West Greenland. Fig 6.1 (29/08/19; top right). A blue/bare-ice zone with surface debris in the western lee of J.A.D. Jensens Nunatakker situated 20 km inland from the ice-sheet edge. Moraine ridges extend along the foot of the nunataks and in one location the moraine is offset by overspilling ice. Ice flowing through a gap in the nunataks has drawn out a lobate moraine ridge that intersects with further ridges down-ice. A lake and a calving margin in ice flowing towards the nunatak occur in an embayment. Fig 6.2 (15/08/19; middle). An outlet glacier, with a bare ice surface, drains westwards from the ice sheet into Melville Bugt at Latitude $75^{0}32'$. Ice flows into several embayments on its northern flank. In one there are five arcuate moraine ridges looping into the embayment each separated by glacier ice; in another is a spread of surface rock debris marked by ridges that also loop into the embayment. Fig 6.3 (28/08/19; lower left). The glacier flowing into Kangilinnquit fjord in southwest Greenland has accumulated debris in embayments adjacent to and facing up-glacier on its southern flank. The pattern of bare ice surface reflects ablation as katabatic winds converge into the outlet glacier catchment and fjord. Fig. 6.4. (23/08/19; lower right) Retreat of Jakobshavn Isbrae since the 1880s reveals morainic and lake deposits in an embayment on the southern flank of the glacier. The debris contrasts with the surrounding ice-moulded bedrock. Inset shows location of the site on the flanks of the fjord covered in brash ice. All images are Copernicus Sentinel data (2019). We thank Mikis van Boeckel for preparing this diagram.

Fig 7. Nextmap image of the Glenmore embayment on the south-eastern flank of the former Strath Spey ice stream that flowed towards the northeast. M1 and M3 mark the margin of two stages of glaciation that encroached into the embayment, depositing a wedge of debris. The photograph in Figure 8 is taken where the Allt Mòr river cuts through the M3 limit.

Fig. 8. Thick Late Pleistocene sediment sequence cut by the Allt Mòr river in the 1960s on the eastern flank of the Glenmore embayment in Strath Spey. The upper till wedge with far-travelled clasts indicates advance of ice from Strath Spey across horizontally-bedded, ice-marginal glacifluvial sands and gravels. An older, buried, lower till with granite clasts is exposed below. Circle indicates a person for scale. Photograph by Sven Stridsberg.

Figures

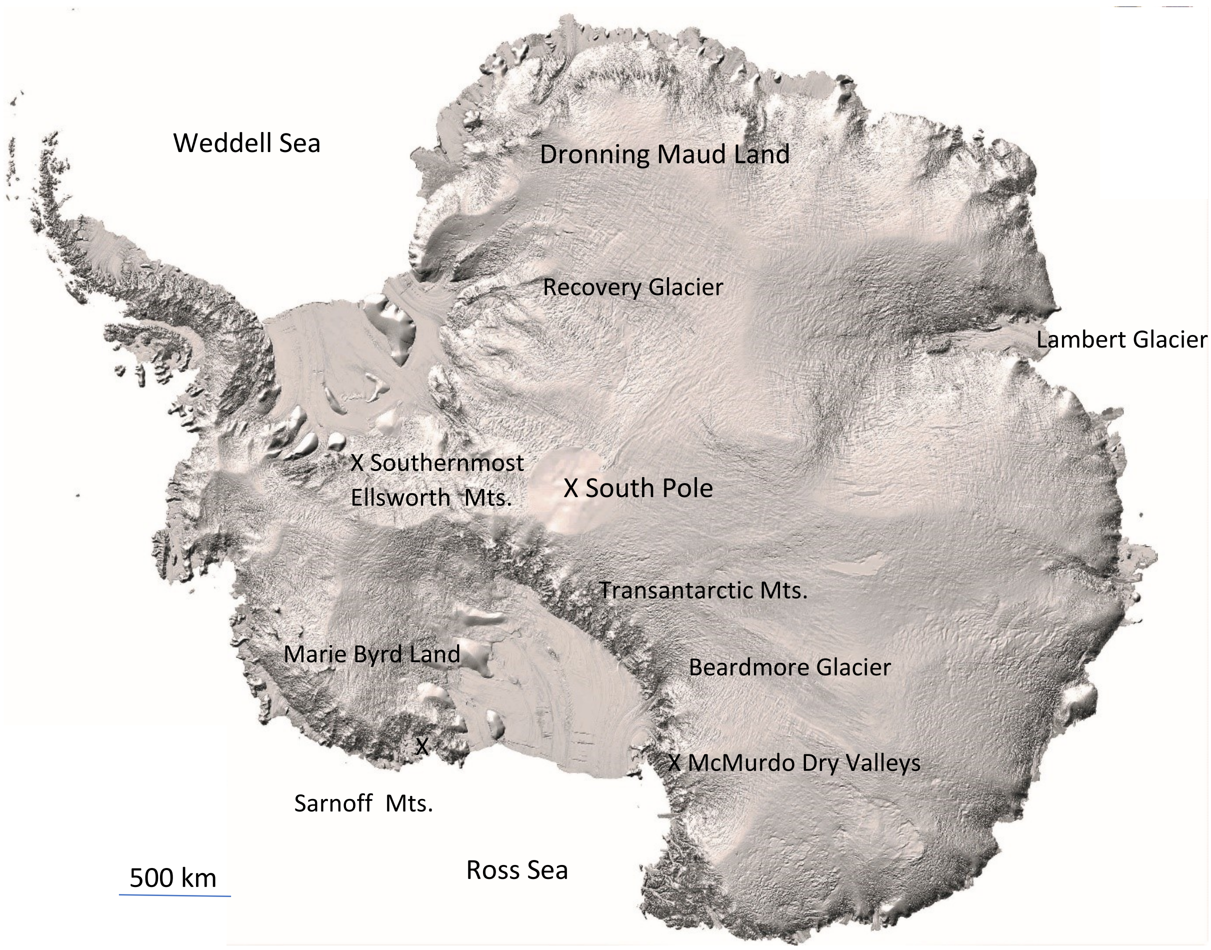

Weddell Sea
Dronning Maud Land
Recovery Glacier
Lambert Glacier
X Southernmost
Ellsworth Mts.
X South Pole
Transantarctic Mts.
Marie Byrd Land
Beardmore Glacier
X
X McMurdo Dry Valleys
Sarnoff Mts.
500 km
Ross Sea

Fig. 1.

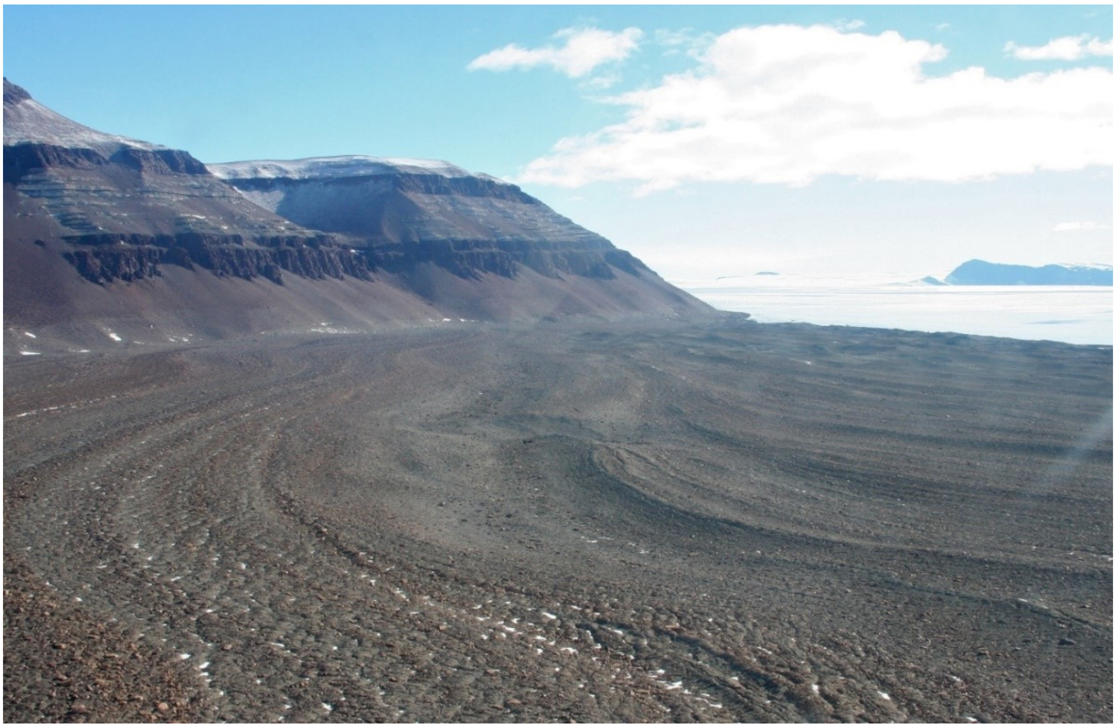


Fig 2

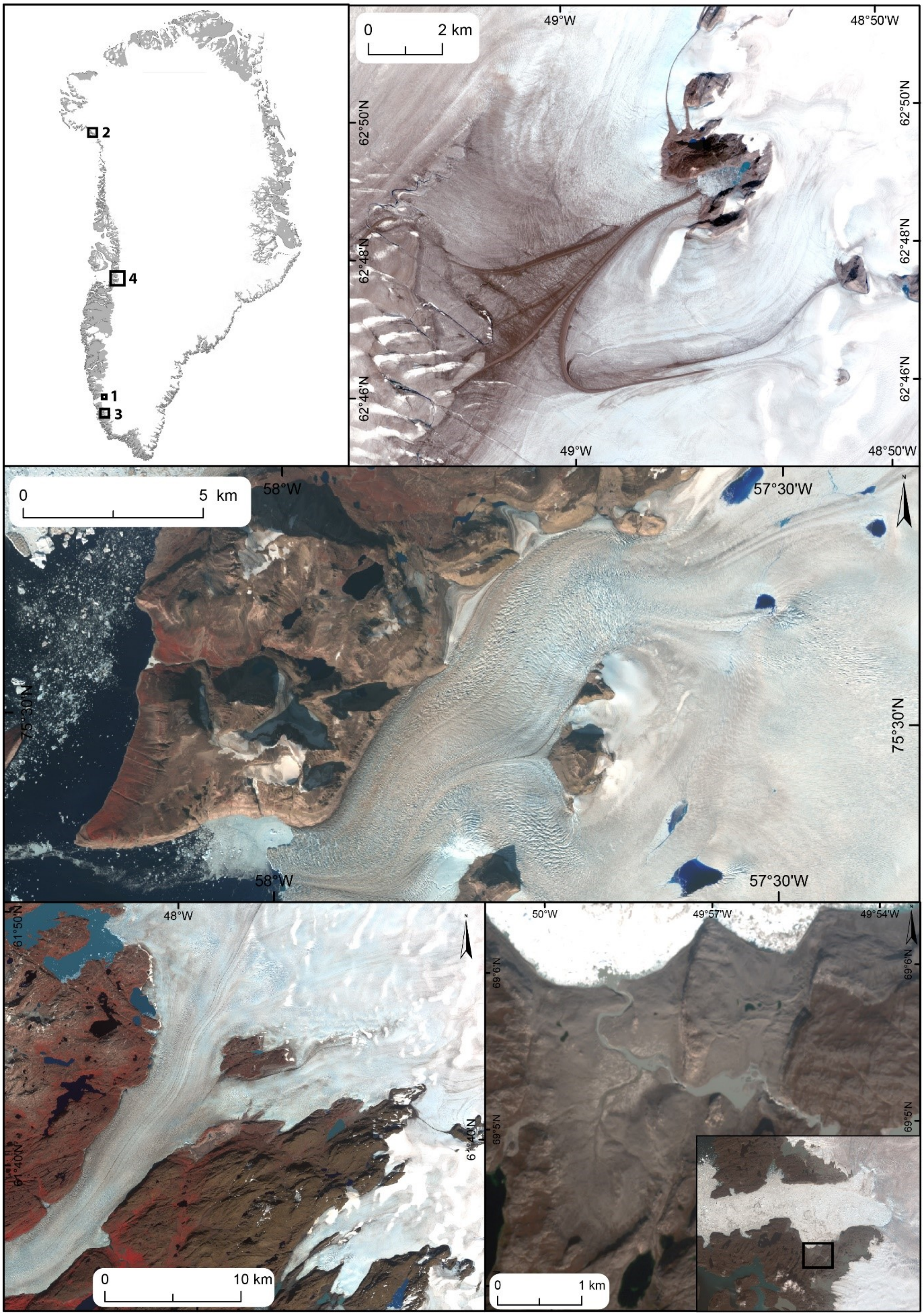
Fig. 3

Fig. 5a. A local corrie moraine exposed in blue ice where it joins a larger glacier, Mt. Gonzalez, Sarnoff Mountains, Marie Byrd Land, Antarctica. Foliation shows that the basal ice of the corrie glacier is exposed on the inboard side of the debris as a result of surface ablation.

Fig 4

Fig. 5a

Fig 5b



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48°50'W
62°50'N
62°48'N
62°46'N
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5 km
58°W
57°30'W
75°30'N
48°W
61°50'N
61°40'N
0
10 km
50°W
49°57'W
49°54'W
69°6'N
69°5'N
0
1 km

Fig 6

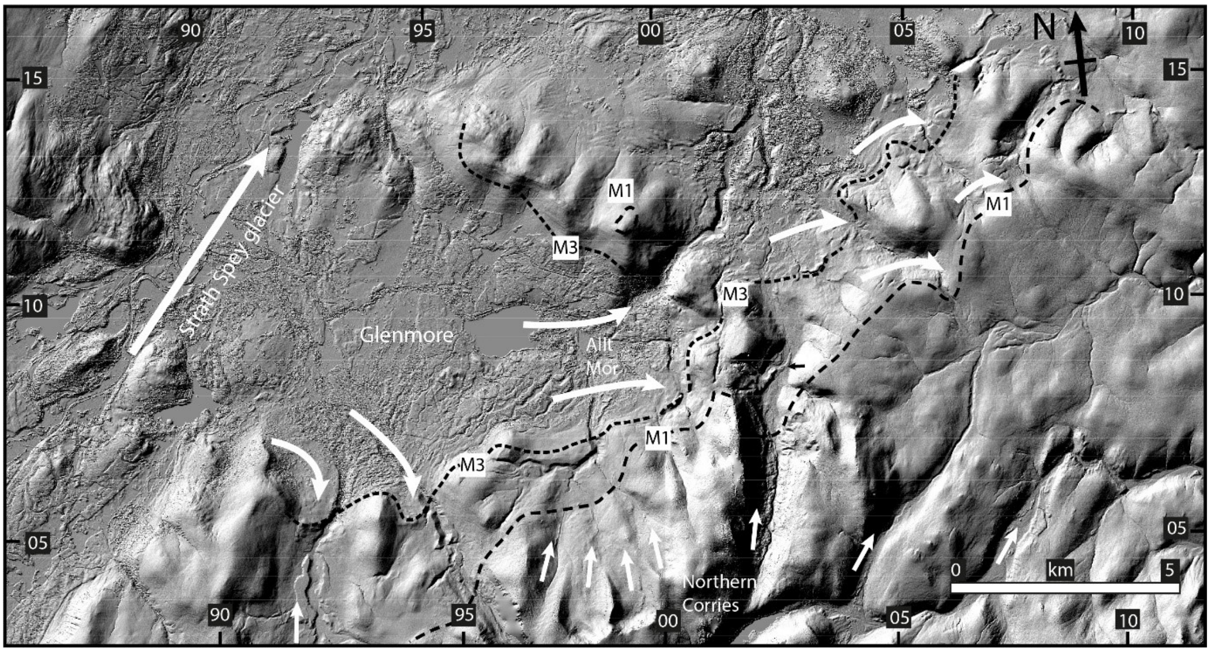
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Fig. 7

Fig. 8